STAFF SUMMARY SHEET

	TO	ACTION	SIGNATURE (Surname), GRADE AND DATE		TO	ACTION	SIGNATURE (Surname), GRADE AND DATE
1	DFC	sig coord	Van Valkaburg, C6, 1 Apr 13	6			
2	DFER	approve	Kraus, Col 3 Apr 13	7		add distribution statement	
3	DFC	action		8			
4				9			
5				10			

SURNAME OF ACTION OFFICER AND GRADE	SYMBOL	PHONE	TYPIST'S INITIALS	SUSPENSE DATE
Dr. Iacono/AD-23	DFC	333-6005	sti	20130415

SUBJECT		DATE
Clearance for Material for Public Release USAFA-DF-PA- 269		20130326

SUMMARY

1. PURPOSE. To provide security and policy review on the document at Tab 1 prior to release to the public.

2. BACKGROUND.
Authors: Cynthia A. Corley and Scott T. Iacono

Title: A Novel Approach to Isolating Nitroexplosives from Imidazolium and Pyrolidinium Ionic Liquid Solutions Using Solid Phase Extraction (SPE)

Circle one: Abstract   Tech Report   Journal Article   Speech   (Paper)   Presentation   Poster

Thesis/Dissertation   Book   Other: _____

Description: A simple solid phase extraction (SPE) sample preparation method is described for isolating nitroaromatic compounds from solutions containing ionic liquids prior to analysis. High recoveries of the compounds of interest are achieved with substantial removal of the ionic liquid, thus avoiding significant interferences and time-consuming and costly instrumental problems.

Release Information: Journal of Analytical Chemistry (ACS Publications)

Previous Clearance information: N/A

Recommended Distribution Statement: (Distribution A, Approved for public release, distribution unlimited.)

3. DISCUSSION. N/A

4. VIEWS OF OTHERS. N/A

5. RECOMMENDATION. Department Head or designee reviews as subject matter expert. DFER reviews for policy and security. Coordination indicates the document is suitable for public release. Suitability is based on the document being unclassified, not jeopardizing DoD interests, and accurately portraying official policy [Reference DoDD 5230.09]. Release is the decision of the originator (author). Compliance with AFI 35-102 is mandatory.

Scott T. Iacono, PhD, USAF
Associate Professor & Director, Chemistry Research Center
Department of Chemistry
US Air Force Academy

1 Tab
Manuscript

AF IMT 1768, 19840901, V5   PREVIOUS EDITION WILL BE USED.

A Novel Approach to Isolating Nitroexplosives from Imidazolium and Pyrolidinium Ionic Liquid Solutions Using Solid Phase Extraction (SPE)

Cynthia A. Corley* and Scott T. Iacono

Department of Chemistry and Chemistry Research Center,
United States Air Force Academy, USAF Academy, CO 80840

ABSTRACT

In recent years ionic liquids have received considerable attention as ideal green solvents for synthesis and extraction applications. Ionic liquids, because of their unique set of properties such as low volatility, high stability, excellent solvation ability, high ionic strength, and tunable structure, are frequently utilized as alternate environmentally friendly solvents to conventional solvents. It is these same properties, however, that present analytical challenges, particularly with liquid chromatography (LC) or gas chromatography (GC) analysis of compounds of interest dissolved in ionic liquid media. A simple solid phase extraction (SPE) sample preparation method is described for isolating nitroexplosive CBRNE compounds from solutions containing 1, 2-dimethyl-3-propylimidazolium bis(trifluoromethylsulfonyl)imide (DMPIm-NTf$_2$) or 1-methyl-3-butylpyrolidinium bis(trifluoromethylsulfonyl)imide (BMPy-NTf$_2$) prior to analysis. High recoveries of the compounds of interest are achieved with substantial removal of the ionic liquid, thus avoiding significant interferences and time-consuming and costly instrumental problems.

INTRODUCTION

Ionic liquids, because of their many unique properties, have attracted considerable interest across many fields of chemistry for use in a wide range of applications. Their versatility is largely due to their ability to be "tuned" with the appropriate combination of cation and anion to influence their physical properties [1,2]. They are frequently utilized as alternate environmentally friendly solvents to conventional solvents in chemical processes including organic synthesis and catalysis, biomass dissolution and biocatalysis, and extraction [3--10]. Ionic liquids have large electrochemical windows, high thermal stabilities, and good conductivity that is desirable for electrochemical applications in lithium-ion secondary batteries, dye-sensitized solar cells, and supercapacitors [11-13]. Ionic liquids have also attracted much interest among chromatographers with the emergence of supported ionic liquid stationary phases for sorptive solid – liquid extractions and separations [14,15].

Solid Phase Extraction (SPE) columns or cartridges and discs have been commercially available since the late 70's for the removal of impurities, isolation of substances of interest, and concentration of samples. SPE is the most widely-used sample preparation technique used for the purification of a variety of compounds prior to analysis [16]. The commercial availability of SPE columns has expanded to include a variety of sorbent properties and configurations including mix-mode sorbents and specialized sorbents with modified silica or polymeric surfaces that enhance sorbent selectivities and optimize extractions for the preparation of samples for analysis [17, 18].

Historically, GC/MS (gas chromatography-mass spectrometry) has been the preferred method for identification of small molecules [19]. GC analysis requires vaporization of the

sample upon introduction into the GC inlet in order to be detected. This creates a problem when analyzing samples containing ionic liquids with very low volatilities and high viscosities. LC and LC/MS (liquid chromatography-mass spectrometry) have also evolved as powerful tools for identifying and quantifying compounds of interest. Contrary to GC/MS, low concentrations of ionic liquid in the LC mobile phase have been found to be excellent ion pairing agents for affecting the free silanol groups of the silica resins that would otherwise interact with basic analytes [20, 21]. However, introduction of significant amounts of ionic liquid into the LC system can also lead to destructive adsorption of the ionic liquid, degradation of the column performance, and contamination of the instrument.

To effectively utilize LC/MS and GC/MS for the analysis of compounds dissolved in ionic liquid media, it is necessary to remove the interfering ionic liquids before analysis. A solid phase extraction method was developed for the concurrent removal of imidazolium or pyrolidinium ionic liquid cation and anions from sample solutions and the recovery of neutral nitroexplosive compounds. The eluate, void of ionic liquid cations and anions, can be collected and analyzed by liquid or gas chromatography without concern for significant interferences and time-consuming and costly instrumental problems.

EXPERIMENTAL SECTION

Materials: The ionic liquids, DMPIm-NTf$_2$ and BMPy-NTf$_2$, were purchased from Sigma-Aldrich (St. Louis, Missouri, USA) and TCI America (Portland, OR), respectively. The solvents, reagents, and individual explosive chemicals were also obtained from Sigma- Aldrich. The explosive mix standard solution (p/n ERE-042) was acquired from Cerriliant Corporation (Round Rock, Texas, USA). The SPE columns (STRATA®-XC strong cation exchange p/n 8BS029-TAK and STRATA®-SAX

strong anion exchange p/n 8B-S008-EAK) and the SPE vacuum manifold were purchased from Phenomenex (Torrance, California, USA). The reversed-phase columns utilized in the LC separations, the Phalanx C18 (5um, 2.5 x 150mm) and the Synergi MAX-Polar (mixed-bed, 2.5um, 2.5 x 100 mm), were acquired from Higgins Analytical (Mountain View, California, USA) and Phenomenex, respectively. Finally, the GC column used for the GC analyses (HP-5MS, 5% Phenyl, 30 ft x 0.25 mm ID) was purchased from Agilent Technologies (Santa Clara, California, USA).

Instrumentation: A Buchi R215 rotary evaporator (Flawil, Switzerland) was used for the removal of the solvents. The samples were analyzed using a 5975C GC/MS with an electron impact ionization source and/or a G1969 ESI-LC/MS-TOF consisting of a gradient LC system coupled to a time-of-flight mass spectrometer and electrospray ionization source. Both chromatography systems are manufactured by Agilent Technologies (Santa Clara, California, USA).

Solid Phase Extraction: The SPE method employs a dual ion exchange separation whereby both anion exchange and cation exchange sorbents are combined for each extraction for the simultaneous removal of the ionic liquid ions. A one- or two-column SPE configuration was utilized for the extractions. For the one-column configuration, the sorbents of the STRATA®-SAX (100 mg bed size) and STRATA®-XC (30 mg bed size) were packed in a single column with the anion exchange sorbent stacked on top of the cation exchange sorbent. For the two-column configuration, the individual ion exchange columns were coupled together via a coupling adapter (Figure 1). It should be noted, however, that both SPE configurations gave

identical results and that the two-column configuration was used for most of the experiments simply because of ease of experimental set-up.

A stopcock between the column assembly and the vacuum manifold allowed regulation of the eluent flow (approximately 2 drops/sec) while the manifold was maintained under vacuum between −20 to −30 in Hg. The column assembly was conditioned with at least 3 mL of methanol. 1 mL of sample solution was loaded onto the column assembly immediately after the conditioning step to avoid drying of the sorbent. The sample was eluted with 1 or 2 mL of methanol, collected, and analyzed by LC/MC or GC/MS to determine the % recovery of the analytes and % removal of the ionic liquid ions. The used SPE column assembly can be washed further with 1 to 2 mL of 0.1 M NaCl and methanol (10:90 v/v) to completely remove the ionic liquid ions adsorbed on the sorbent surface. This process allows for regeneration and reuse of the columns. All the samples collected from the extractions were diluted with methanol or concentrated as needed before analysis by LC/MS-TOF and GC/MS.

Instrumental Analysis: The analytes and ionic liquid solutions were dissolved in methanol with concentrations of 10–200 ug/mL and 2–3 mg/mL, respectively, unless otherwise noted. The ionic liquids were added to the sample solutions to obtain final analyte to ionic liquid weight ratio of 1:50 (w/w). The eluate from the extractions were diluted an additional 1:10 (v/v) with methanol for the LC/MS analyses. A gradient elution from 30% to 80% organic composition was employed for the reversed-phase LC separations. The mobile phase consisted of 5 mM ammonium formate and methanol. For the GC/MS samples, the eluate from three extractions were combined, dried down with N_2 purging, and reconstituted in 1 mL of methanol then

injected into the GC. The GC oven temperature was ramped at a rate of 20 $^{\circ}$C min^{-1} from 70 $^{\circ}$C to 280 $^{\circ}$C.

RESULTS AND DISCUSSION

A non-retentive ion exchange solid phase extraction method was developed for the removal of 1,2-dimethyl-3-propylimidazolium bis(trifluoromethylsulfonimide) (DMPIm-NTf$_2$) and 1-methyl-3-butylpyrolidinium bis(trifluoromethylsulfonyl)imide (BMPy-NTf$_2$) ionic liquids from the sample matrix to isolate and purify explosive compounds. The chemical structures of the compounds examined are illustrated in Table 1.

Typical ion exchange sorbents contain hydrophilic functional groups bonded to a silica or polymeric resin that can exchange with the free anions or cations in the sample solution. In conventional non-retentive ion exchange SPE, aqueous samples are introduced into pre-conditioned anion or cation exchange columns and the compound(s) of interest are eluted and collected. The SPE method described utilizes a combination of strong anion exchange and strong cation exchange sorbents to allow for exchange of DMPIm-NTf$_2$ or BMPy-NTf$_2$ anions and cations in a single non-aqueous non-retentive extraction.

Removal of the ionic liquid: The significance of the removal of the ionic liquid ions in sample solutions is realized in the severe tailing peaks observed for the ionic liquid by LC/MS analysis, particularly in the positive mode (Figures 2A and 3A). Problems with carryover of the ionic liquid to subsequent runs made identification and quantitation of trace compounds near impossible, necessitating a sample preparation step to remove the interfering ionic liquid from the sample solution prior to analysis.

Figures 2 and 3 illustrate the LC/MS-TOF extracted ion chromatograms (EIC) of sample solutions containing DMPIm-NTf$_2$ and BMPy-NTf$_2$, respectively, before and after solid phase extraction (m/z = 139-140 for DMPIm$^+$, m/z = 142-143 for BMPy$^+$, and m/z = 279-280 for NTf$_2^-$). The amount of ionic liquid ions removed after solid phase extraction were found to be >95% for DMPIm$^+$, BMPy$^+$ and NTf$_2^-$ provided the ionic capacities of the ion exchange sorbents were not exceeded for each extraction. The breakthrough mass for DMPIm$^+$ ion with the STRATA®-CX column was determined to be ca. 4.0 mg. The observed value is in close agreement to the theoretical value of 4.17 mg which suggests the interaction between DMPI$^+$ and the benzylsulfonic acid mixed-mode functionality of the sorbent is primarily ionic. In consequence, the breakthrough mass for DMPIm$^+$ was reduced when competing cations were present in the sample matrix (Figure 4). Similar results were observed for BMPy$^+$.

The method described was also observed to be easily scalable to larger sorbent bed sizes to enable removal of higher concentrations of ionic liquid in the sample media. The % removal of the ionic liquid was found to be comparable to those observed for the smaller bed size columns. Other SPE sorbents including weak cation exchange, weak anion exchange, and C18 reversed-phased sorbents were also examined for the removal of ionic liquids. However, the % removal calculated for the experiments were very poor (< 35%).

Recovery of the explosive compounds: Sample solutions of explosives in ionic liquid media were prepared, extracted, and analyzed by GC/MS or LC/MS-TOF. The explosives, with the exception of 2-amino-3,5-dinitrotoluene, 3-amino-1,5-dinitrotoluene, RDX and Tetryl, were effectively isolated by SPE and confirmed by GC/MS analysis with match values of > 95%.

The compounds retained on the SPE columns are all amino-aromatic explosives (designated with a * in Table 1). Amines are notorious for interacting with free silanol groups on the sorbent surface by hydrogen bonding [19,20]. And since the STRATA®-SAX column employs a silica-based sorbent, it would certainly be the most credible explanation. To test this theory, sample solutions of the amino explosives in methanol were eluted through each of the ion exchange columns separately then analyzed by GC/MS. Correspondingly, the compounds were recovered from the STRATA®-XC column (polymeric-based sorbent) and were fully retained on the STRATA®-SAX column. Regrettably, a polymeric-based strong anion exchange column (e.g. Phenomenex STRATA®-XA) was not available for testing at the time of this study but is certainly worth investigating for the sample preparation of amino compounds in ionic liquid media.

The % recoveries of three explosive compounds (2,4-dinitrotoluene, trinitroluene, and 1,3-dinitrobenzene) were determined to be > 85% when the analyte to ionic liquid weight ratio was 1:50 (w/w). Additional experiments showed that the recoveries of the explosives increased proportionally with the increase of ionic liquid concentration until the ionic capacities of the SPE sorbents were exceeded, beyond which point the ionic liquid signal often masked or interfered in the detection of the analytes. It would stand to reason that interactions between the neutral explosives and available active sites on the ion exchange surfaces must also exist. The likely interaction mechanism would involve π-π bonding or hydrophobic interaction with the benzyl functionality of the cation exchange sorbent. Quantitation of the analytes after SPE treatment was not straightforward due to analyte/sorbent interactions, especially when the sample solutions contained large analyte-to-ionic liquid concentration variability. However

when the ratio variability was minimized or taken into account for a given set of samples, excellent linearity was achieved with correlation coefficient values (R^2) of 0.9998 and 0.9971 for dinitrobenzene and trinitrotoluene, respectively.

CONCLUSIONS

Analyzing sample solutions containing ionic liquids by LC/MS or GC/MS can be a challenging task due to interactions associated with the ionic liquid that can lead to poor chromatography and instrumental problems. Ion exchange SPE is one of the oldest chromatographic techniques for desalting and removal of ionic impurities or interferences and continues to evolve as new sorbents, applications, and configurations are developed even to this day. In this study, a novel SPE ion exchange method is introduced that incorporates both cation and anion exchange sorbents in a single extraction for the removal of interfering ionic liquid and isolation of neutral explosive compounds prior to analysis. With this method, > 95% removal of DMPIm-NTf$_2$ or BMPy-NTf$_2$ in the sample matrix can be achieved, allowing for problem-free analysis of compounds of interest.

AUTHOR INFORMATION

*Email: cynthia.corley@usafa.edu (C.A.C)

ACKNOWLEDGMENTS

REFERENCES

(1)   Koel, M. *Ionic Liquids in Chemical Analysis*; CRC Press: Florida; 2009.

(2)   Manohar, C. V.; Banerjee, T.; Mohanty, K. *J. of Mol. Liq.,* **2013**, 180, pp 145-153.

(3)   Mohammad, A.; Inamuddin *Green Solvents II: Properties and Applications*; Springer: New York; 2012.

(4)   Gonzalez, B.; Corderi, S.; Santamaria, A. G. *J. of Chem. Thermodynamics* **2013**, 60, pp 9-14.

(5)   Breeden, S. W.; Clark, J. H., Macquarrie; D. J., Sherwood, J.; Zhang, W.; Berkeley, W. Jr. *Green Techniques for Organic Synthesis and Medicinal Chemistry* **2013**, pp 243-261.

(6)   Das, R.; Narayan, R.; Kunal *Mol. Diversity,* **2013**, *17*, pp 151-196.

(7)   Phan, T. S. N.; Le, V. H.; Nguyen, T. A. *Tap Chi Hoa Hoc,* **2012**, 50, pp 126-131.

(8)   Rao, M. S.; Chhikara, B. S.; Tiwari, R.; Shirazi, A. N.; Parang, K.; Kumar, A. *Chemistry & Biology Interface*, 2012, 2, pp 362-372.

(9)   Oromi-Farrus, M.; Eras, J.; Sala, N.; Torres, M.; Canela, R. *Molecules*, 2009, 14, pp 4275-4283.

(10)   Borrull, F.; Marce, R. M. *Trends in Anal. Chem.,* 2012, 41, pp 15-26.

(11)   Zein El Abedin, S.; Ryder, K. S.; Hoefft, O.; Farag, H. K. *Intl. J. of Electrochem.,* 2012, 978060, pp 2.

(12)   Wang, M., Shan, Zhong-qiang *Xin Cailiao Chanye,* 2012, 9, 31-37.

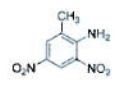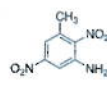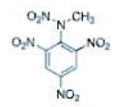(13)   Xiang, J.; Wu, F.; Chen, R.; Li, L.; Yu, H. *J. of Power Sources,* 2013, 233, pp 115-120.
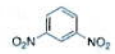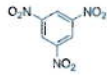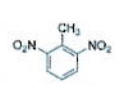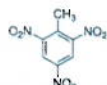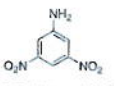
(14) Shu, J.; Li, C.; Liu, M.; Liu, H.; Feng, X.; Tan, W.; Liu, F. *Chromatographia,* 2012, 75, pp 1421-1433.

(15) Zhao, S.; Zhang, L. *Huaxue Tongbao,* 2012, 75(11), pp 1001-1008.

(16) Thurmal, E.M.; Mills, M.S. *Solid-Phase Extraction: Principles and Practice*; John Wiley & Sons: New York; 1998.

(17) Kole, P. L.; Venkatesh, G.; Kotecha, J.; Sheshala, R. *Biomedical Chromatography,* 2011, 25, pp. 199-217

(18) Ming-Ming, Z.; Ge-Deng, R.; Yu-Qi, F. *J. of Chrom.,* 2009, 1216(45), pp 7739-7746.

(19) McNair, H.M.; Miller, J. *Basic Gas Chromatography*; John Wiley & Sons: New Jersey; 1998.

(20) Petruczynik, A. *J. of Chrom. Sci.,* 2012, 50, pp 287-293.

(21) Ahmad, T.; Smith, S.; Redlinski, B.; Utterback, C.; Perkins, D.; Sharp, S.; Heagy, A.; Ahmad, T. *Adv. in Anal. Chem.,* 2012, 2, pp 60-66.
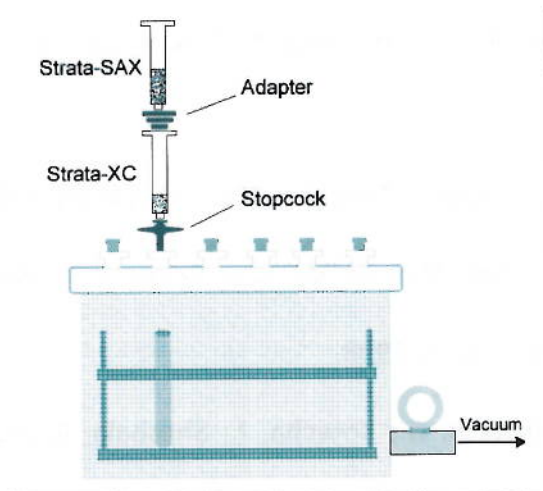
Figure 1: SPE column assembly with SPE vacuum manifold

**Table 1:** Chemical structures of the compounds examined

Ionic Liquids

DMPIm-NTf2[†]
1, 2-dimethyl-3-propylimidazolium
bis(trifluoromethylsulfonyl)imide

BMPy-NTf2[†]
1-methyl-3-butylpyrolidinium
bis(trifluoromethylsulfonyl)imide

Explosives

Nitrobenzene

1,3-dinitrobenzene

1,3,5-trinitrobenzene

2-nitrotolune

3-nitrotolune

4-nitrotoluene

2,4-dinitrotolune

2,6-dinitrotoluene

2,4,6-trinitrotolune (TNT)

3,5-dinitroaniline[†]

2-amino-3,5-dinitrotolune[†]

3-amino-1,5-dinitrotolune[†]

1,3,5-trinitroperhydro-1,3,5-triazine (RDX)[†]

N-methyl-N-2,4,6-tetranitroaniline (Tetryl)[†]

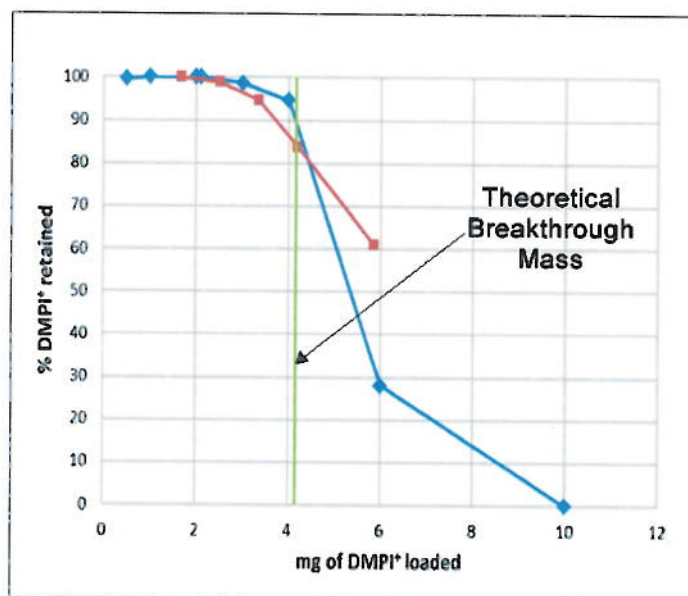[†]Retained on the STRATA-SAX/STRATA-XC column assembly
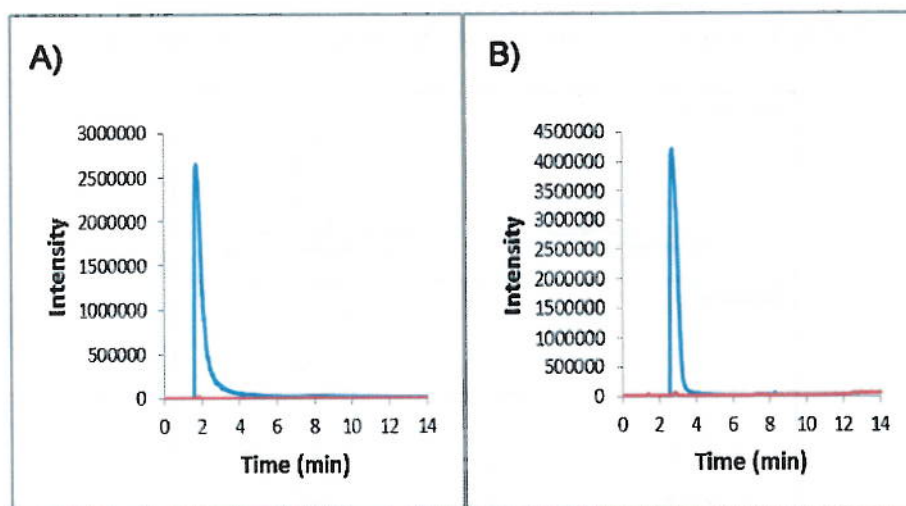
Figure 2: Extracted Ion Chromatograms (EIC) of DMPI-Tf$_2$N before (blue) and after (red) SPE in the positive (A) and negative (B) MS mode.
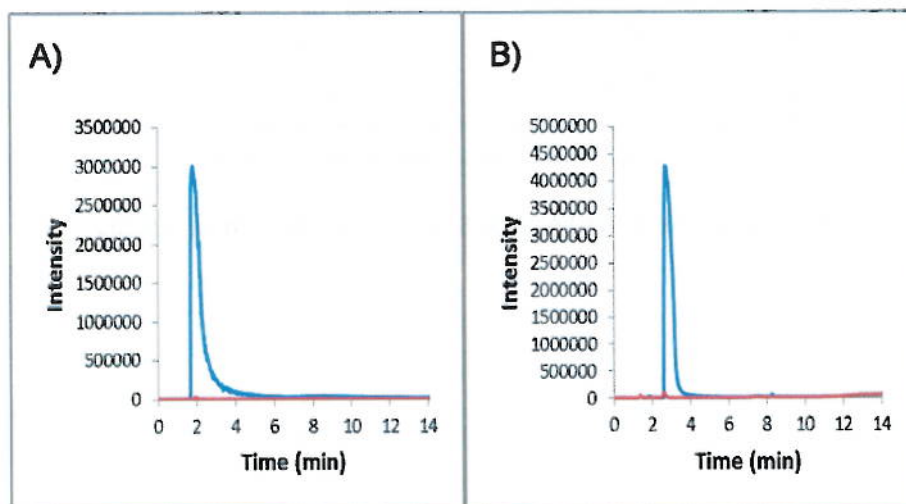
Figure 3: Extracted Ion Chromatogram (EIC) of BMPyr-Tf$_2$N before (blue) and after (red) SPE in the positive (A) and negative (B) MS mode.

Figure 4: Retention of DMPI$^+$ on the Strata-XC SPE column: (◆) Ionic liquid only, (■) Ionic liquid with 8.0 wt% tetramethylammonium hydroxide.